Energy confinement in the TM-G tokamak at high plasma densities

A. M. Stefanovskiĭ
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 28 Arpil 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 11, 515–518 (10 June 1986)

It is concluded from an analysis of experimental data obtained from the TM-G and other tokamaks that the dependence $\tau_E(n_e)$ reaches saturation at high densities because of a contraction of the current channel and a disruption of the "self-consistent" current profile. Another important factor may be the excitation of drift waves at densities near the Murakami limit.

The dependence of the energy confinement time τ_E on the plasma density in a tokamak, particularly the saturation which sets in at high densities, has recently been discussed extensively in the literature.[1] This saturation was originally attributed to the effect of ion heat transfer and an inadequate ohmic-heating power, but later experiments with auxiliary plasma heating revealed that the tendency toward saturation persists, while the dependence of τ_E on other parameters of the tokamak becomes completely different.[2] Since the scaling of τ_E is of primary importance for choosing the parameters of a tokamak reactor, it remains a matter of major interest to determine the reasons for the saturation of $\tau_E(n_e)$.

0021-3640/86/110666-05$01.00

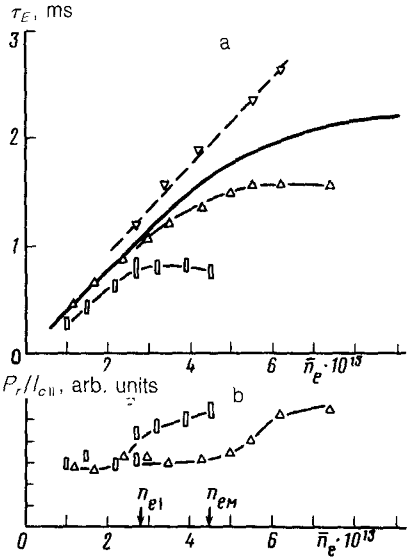

FIG. 1. a: Solid line—calculated values of τ_E for $I_p = 20$ kA; ▯—experimental, $I_p = 20$; Δ—experimental, $I_p = 40$ kA; ∇—experimental, $I_p = 60$ kA; b: ratio of the radiative-loss power P_r to the flux of carbon atoms from the wall ($\sim I_{c\,II}$).

We have accordingly used the TM-G tokamak, with an all-graphite discharge chamber,[3] to measure the energy confinement time τ_E at various plasma densities in three distinct discharge regimes with an identical value of the safety factor at the limiter ($q_L = 3$) but different values of the discharge current and of the longitudinal field ($I_d = 20$, 40, and 60 kA; $B_T = 0.8$, 1.6, and 2.4 T). The results of these measurements are shown in Fig. 1a. On the whole, these results are typical of tokamaks. Distinctive features are that the scanning of the discharge parameters was carried out over a broad B_T range and that the value of z_{eff} at a low plasma density in the TM-G was approximately unity: $1 - 1.2$ at $n_e = 2.4 \times 10^{13}$ cm^{-3} and $1.4 - 1.5$ at $n_e = (6 - 7) \times 10^{13}$ cm^{-3}. Since carbon was the only impurity in the plasma, we ignored radiative loss in the calculation of τ_E. Among the important results we note that the value of τ_E / n_e is not constant in the different discharge regimes and is roughly proportional to $\sim B_T^{1/2}$ as can be seen from Fig. 1a. This result means that $\langle T_e \rangle$ (or T_{e0}) is proportional to B_T. The central electron temperatures measured at a low density in the regimes with $I_d = 40$ and 60 kA are 480 and 700–750 eV and agree with $T_{e0} \sim B_T$.

Let us consider some of the reasons for the saturation of $\tau_E(n_e)$ at high plasma densities. We will first estimate the role of ions in the thermal insulation of the plasma. Figure 1a shows the results of a model-based calculation of the energy balance in the TM-G, carried out under the assumption of a neoclassical ion behavior and a thermal conductivity of the T-11 type[4] for electrons, for $J_p = 20$ kA. We see that the calculated and experimental results on τ_E as a function of the plasma density differ not only in the point at which the behavior $\tau_E(n_e)$ changes but also in the nature of τ_E above this point. We will thus discuss some other possible reasons for the saturation of $\tau_E(n_e)$: a contraction of the current channel of the plasma and the appearance of an elevated heat transfer in the plasma at a certain plasma pressure β_J^*.

The contraction of the current channel in the TM-G was detected from the nature of the change in the peripheral radiative loss with increasing plasma density. Figure 1b shows $P_r/I_{c\text{II}}$, the power of the radiative loss, divided by the flux of carbon atoms from the wall into the plasma. It was shown beforehand that $I_{c\text{II}}$, the intensity of the emission in the line of the C^{+1} ion, is determined exclusively by the flux of carbon atoms from the wall and does not depend on the plasma density. The change in $P_r/I_{c\text{II}}$ at a certain n_{e1} is evidence of a change in the profile $T_e(r)$, i.e., of a contraction of the current channel. It should be noted that a "detachment" of the current channel from the limiter (or separatrix) has also been observed in other tokamaks. In Ref. 5, for example, it was observed in situations with $q_L > 2.7$, and in Ref. 6 at $q_L \simeq 2.5$. It can thus be assumed that the contraction of the current channel in tokamak discharges at an elevated density occurs in all situations with $q_L \gtrsim 2.5$. The contraction of the current channel probably continues until, at the maximum attainable density n_{eM}, the value of q_I at the boundary of the current channel becomes nearly equal to 2; at this point, a large-scale MHD instability of the plasma can set in (and proceed to the point that the current is cut off). The final radius of the current channel in this state can easily be determined from the condition $q_I = 2$:

$$a_{I\,min} \approx R\sqrt{\frac{2I_p}{I_T}}\,, \tag{1}$$

where I_T is the total current in the toroidal coils of the tokamak. On the other hand, we know quite well that in discharges with $q_L < 2.5$–3 the energy-confinement time in the plasma decreases in proportion to q_L; this effect is usually attributed to a disruption of the "self-consistency" of the plasma current profile in terms of the electron heat transfer and a partial disruption of the magnetic configuration due to a tearing-mode instability. Similar effects should evidently occur during the contraction of the current channel, since q_I decreases in this case from the initial value q_L to 2. The disruption of the "self-consistent" current profile in the final stage of the contraction of the current channel may thus be a reason for the saturation of $\tau_E(n_e)$.

There are several effects capable of causing a contraction of the current channel: a redistribution of the energy fluxes between electrons and ions, an emission by light impurities, a charge exchange of the cold gas incident on the plasma, and the onset of various dissipative instabilities. All these effects could play an important or even key role in real experiments and could contribute to the contraction of the current channel. The cause of the contraction, however, might also be the existence of a certain plasma pressure at the given distribution of the current (or of β_I^*) at which an elevated heat transfer begins in the plasma. It is easy to see that a contraction of the plasma column leads to a decrease in β_I and to the disappearance of this transfer in the plasma. Because of current conservation ($a^2T_e^{3/2} \simeq \text{const}$), we find, at a given density, $\beta_{I2} = \beta_{I1}(a_2/a_1)^{2/3}$; i.e., the value of β_I after the contraction is lower than that before the contraction.

A saturation of $\tau_E(n_e)$ is observed in the TM-G at plasma densities $n_e > n_{e1}$, i.e., essentially immediately after the contraction of the current channel. The density n_{e1}, which is 0.6 to 0.7 of n_{eM}, corresponds well to the relation of Hugil's diagram:

$$n_{eM} \lesssim 5-10\times10^{11} B_T\,(\text{G})\,/R\,(\text{cm})\,q_L = 1-2\times10^{11} I_p(A)/a^2\,(\text{cm}^2). \tag{2}$$

This inequality obviously imposes a lower limit on the electron current velocity u_T: $n_{eM} \lesssim (1\text{–}2)\times 10^{11}\pi e n_{eM} u_T$ or $u_T > v_n = (1\text{–}2)\times 10^{7}$ cm/s. If the processes which determine the "detachment" of the current channel from the limiter at $n_e = n_{e1}$ and the current disruption at $n_e = n_{eM}$ are of the same nature, an inequality analogous to (2) should hold for the density n_{e1}. Of all the characteristics plasma velocities in the TM-G, only the sound velocity, the ion thermal velocity, and the longitudinal velocity of drift waves satisfy inequality (2). For the drift waves, in particular, we find

$$v_{\| d} = \frac{R}{n}\frac{m}{r}\frac{c}{B_T}\frac{1}{en_{e1}}\frac{dp_e}{dr} \lesssim \frac{j_z}{en_{e1}} . \tag{3}$$

It can be seen from this inequality that we are dealing with waves with a large azimuthal index $m(k_\varphi \approx m/r)$ and a minimum (~ 1) index $n(k_\| \approx n/R)$. It can also be seen that the conditions for a resonant interaction of the current with drift waves $(u_T \approx v_{\|d})$ depends on the radius r and is manifested primarily at the plasma periphery as the pressure is raised (this effect might also lead to a contraction of the current channel). To estimate the coefficients in inequality (3), we use the average values:

$$n_{e1} \lesssim \frac{I_p}{\pi e a^2}\frac{eB_T}{cT_{e0}}\frac{a}{R}\frac{r}{m} . \tag{4}$$

Substituting the value T_{e0} (eV)$/B_T(G) = 3\times 10^{-2}$, measured in the TM-G, and the parameters of this device $(R/a = 5)$ into (4), we find

$$n_{e1} \lesssim 1.3\times 10^{11}\frac{I_p}{a^2}\frac{r}{m} . \tag{5}$$

If we have $r/m \approx 1$ (three or four times the ion Larmor radius in the TM-G) in (5), the agreement with the measured value of n_{e1} turns out to be quite good. In the state of greatest contraction of the current channel, the quantity a^2 is no longer independent, so that (4) gives us the following expression for n_{eM}:

$$n_{eM} \lesssim 6.5\times 10^{11}\frac{I_p}{a^2}\frac{a}{R}\sqrt{\frac{q_L}{2}} . \tag{6}$$

Inequality (3) can formally be put in the form $\beta_{Ie} < \beta_I^*$, so that relations (4)–(6) may be thought of as a restriction on β_{Ie}, above which drift waves are excited at the plasma periphery, the current channel contracts, and the thermal insulation of the plasma is degraded. If the condition $u_T = v_{\|d}$ holds over a broad interval of r, this degradation of the thermal insulation may not be accompanied by a contraction of the current channel.

A second mechanism which might possibly lead to a saturation of the dependence $\tau_E(n_e)$ is thus the resonant excitation of drift waves with $k_\perp \rho_i \sim 1$ and $k_\| R \sim 1$ in the plasma. This excitation would occur at a density near the Murakami limit. If the same mechanism causes the contraction of the current channel, the excitation of drift waves and the disruption of the self-consistent current profile occur simultaneously.

I am deeply indebted to B. B. Kadomtsev for a discussion of this study and to F. G. Merezhkin for carrying out the numerical calculations.

[1] R. J. Goldston, Reprint PPPL-2060, 1984.
[2] S. M. Kaye and R. J. Goldston, Nucl. Fusion **25**, 65 (1985).
[3] E. I. Dobrokhotov, M. M. Dremin, Yu. D. Pavlov, *et al.*, Conf. on Plasma Phys. and Contr. Nucl. Fus. Res., Baltimore, 1982, Proc., Vol. 111, IAEA, Vienna, 1983, 229.
[4] V. M. Leonov, V. G. Merezhkin, V. S. Mukhovatov, *et al.*, Conf. on Plasma Phys. and Contr. Nucl. Fus. Res., Brussels, 1980, Proc., Vol. 1, IAEA, Vienna, 1981, 393.
[5] H. Neidermaier, R. Bartiromo, G. Becker, *et al.*, Contr. Fus. and Plasma Phys., Budapest, 1985, Proc., Part 1, 159.
[6] J. Lingertat, K. F. Alexander, Ch. Grunov, *et al.*, Contr. Fus. and Plasma Phys., Budapest, 1985, Proc., Part II, 559.

Translated by Dave Parsons